Problems in the Forecasting of Solar Particle Events for Manned Missions

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Abstract

Manned spacecraft will require a much improved ability to forecast solar particle events. The lead time required will depend on the use to which the forecast is put. Here we discuss problems of forecasting with the lead times of hours to weeks. Such forecasts arc needed for scheduling and carrying out activities. Our present capabilities with these lead times is extremely limited. To improve our capability we must develop an ability to predict fast coronal mass ejections (CMEs). It is not sufficient to observe that a CME has already taken place since by that time it is already too late to make predictions with these lead times. Both to learn how to predict CMEs and to carry out forecasts on time scales of several days to weeks, observations of the other side of the Sun are required. We describe a low cost spacecraft, MagSonas (SMEX class), that has been proposed for launch in 2001 that will further the development of an hours-to-weeks forecast capability.

introduction

The expected return of human beings to interplanetary space brings new requirements for our ability to predict and forecast hazardous solar particle fluxes and fluences in space and on the surfaces of the moon, Mars and, eventually, other planets. The prediction and forecasting requirements for such missions have recently been reviewed by a workshop on Risk Management, and their findings have been reported in "Foundations of Solar Particle Risk Management Strategies" (1996). Figure 1, adapted from that report, shows the type of forecasts that will be needed and the workshop's assessment of the current capabilities. In this paper 1 focus on forecasting with lead times of 2 to 20 hours and lead times of days to weeks. Forecast lead times of hours arc needed for operations. The current capability is rated as moderate. Day to week forecasts are needed for operational decision making. Examples include deciding if the solar particle environment would bc benign enough in the next one or two weeks to launch a manned spacecraft to the moon without emergency shelt cr availability. Another example is the scheduling of EVA on the space station or during a Mars mission. As the table shows, our current ability to make forecasts on time scales of days to weeks is nonexistent.

High fluxes of solar particles in space are not very unusual. NOAA Space Environment Center defines a Solar Particle Event as a period in which the flux of protons E> 10 MeV exceeds 10 particles/s- cm^{-2}-sr. It is not uncommon to exceed this limit. Figure 2 shows that the average daily flux was above that threshold about 5 % of days (18 days/year) during most of the active years of each solar cycle but 14 % of the days(51 days) in 1989.

Thus it is clearly vital for the scheduling of astronaut activities in space that we develop an ability to forecast hazardous environments on time scales of days to weeks.

in this paper I will briefly review properties of Solar Proton Events (SPE) that contribute to our inability to forecast on these time scales and I will suggest a program to allow us to develop a forecasting procedure in time for usc in the manned space program.

Review of the forecast problem

For many years it was believed that solar particles were accelerated in flares and diffused through the solar corona and thence into the interplanetary medium. More recently it has become clear that the particles of interest for hazard assessment (E> 10 MeV) are accelerated by shocks associated with coronal mass ejections (CMEs) (cf. Gosling, 1993). For further discussion see Reames (this conference). The pertinent shocks form in the corona within a few solar radii of the Sun and continue to accelerate particles as the shocks pass through the solar wind.

A typical interplanetary particle event is shown in figure 3. Note that the particle flux initially increases, reaches a maximum on March 10 and then begins to decrease. The initial increase was due to a CME at 69 E (Feynman and Hundhausen, 1994). A second increase begins near 2300 March 10, clue to a CME that occurred earlier that day. The spike in particle intensity on March 13 corresponds to the arrival of the March 10 CME shock at Earth. The third increase on March 18 was due to a CME associated with a flare at 60 W.

This event is typical of large proton events in several respects of importance for the problem of forecasting on both time scales of hours and the time scales of days to weeks. "]'here were a several successive increases of particle flux, each associated with a separate CME from the same activity center on the Sun. It has often been noted that major SPEs are due to series of events from single active regions (Malitson and Webber, 1962, Feynman et al. 1993). This means that in order to forecast the beginning of a large SPE event we must forecast the easternmost CME in the series.

Another typical feature is that the time between the occurrence of a CME at the Sun and the appearance of particles at Earth is a function of the position of the associated activity center relative to the Earth. Figure 4 shows data on the relation between the position of the activity center and the transit time of the particles from the Sun to the Earth. We note that protons from an active region at 30 W may take as little as 30 minutes to appear at Earth. The method currently in use for forecasting events on time scales of 2 to 20 hours consists of observing solar activity that indicates that a CME has already taken place.

Once indications of a CME is observed a model is used to forecast the arrival time of solar protons (Foundations of Solar Particle Risk Management Strategies, 1996). However, for events beginning anywhere on the western hemisphere of the Sun, figure 4 clearly shows that if we need to forecast an SPE with a lead t imc of more than 2 hours we can not base our forecast on an observation that a CME has already occurred, Once a CME has occurred we can not count on having 2 hours before the particles arrive. The situation is even worse, of course, if a forecast is needed 20 hours in advance. The only event in Figure 4 that would have been predictable on that time scale is due to a CME taking place on the eastern limb of the Sun.

The fundamental difficulty of forecasting SPE on time scales of days to weeks is illustrated in figures 5 and 6. Figure 5 shows the positions of the easternmost CME for 7 major SPEs. The data are from Shea (this conference) and refer to energies >10 MeV. This energy range is most important for unshielded spacecraft systems. Of course the same events will be the most important SPEs for the E>30 MeV range of importance for manned missions. Note that the positions of the easternmost CMEs range from near the eastern limb of the Sun to well into the western hemisphere. For 3 out of the 7 events in this small sample, at the time the easternmost CME of the series was observed, it would have already been too late to make a forecast with a reliable 2 hour lead time, much less a 20 hour lead time. Instead <u>we must develop our ability to predict fast CMEs before they happen.</u>

Figure 6 shows the positions of the first CMEs one week (upper panel) and two weeks (lower panel) before the onset of the SPEs in figure 5. For a 1 week lead time, half the source regions are on the far side of the Sun and for a 2 week lead time, all of the sources are on the far side of the Sun. <u>Thus in order to forecast with a lead time of days to weeks we must be able to observe activity centers on the other side of the Sun and to predict that they will produce a series of CMEs days or weeks later.</u>

A study of the problems inherit in forecasting a major SPE using only data from this side of the Sun was made using the March 1989 SPE as an example (see figure 3). This event was caused by CMEs from a long lived activity center that was present on the Sun during the two solar rotations preceding rotation during which the event took place (for further details see Feynman, 1997). During that time new magnetic flux erupted repeatedly and old flux disappeared. The SPE was initiated by a CME at 69 E during the third return of the region. These observations presented a good opportunity to test our ability to forecast a major SPE event. One might hope, for example, that the observed growth of the activity center during an earlier rotation might be used as an indicator. This did not turn out to be the case. The history of the total flux in the region as a function of time can be estimated from the area of the sunspots in the region. Figure 7 shows the sunspot area at 60 degrees east and west of central meridian; during the two rotations preceding the March event, during the March event itself and during the following rotation. The areas of the sunspots are given in units of 10^{-6} of the visible solar hemisphere.

In the discussion that follows, the rotation in which the March events took place will be referred to as rotation O, the preceding rotations will be called -1, -2. During rotation -2 the sunspot area increased from about 150 to about 1400. Remarkably, in spite of this large quantity of emerging flux, there was only one class M x-ray flare during that rotation. (x-ray events are classified as C, M, and X. C indicates 10^{-6} w/m^{-2} and M and X are each one factor of 10 higher). The area continued to increase while the region was on the far side of the Sun. During disk passage -1 nine x-ray flares of class M or above took place, but no SPE resulted and the sunspot area decreased by about a factor of two, suggest ing that the activity center was exhausting itsel f. It did not seem that the region would return again and certainly there was no reason to forecast a major particle event on time scales of weeks. However, while on the far side of the Sun the activity center must have grown rapidly. Even before the spot groups had come over the Eastern limb a series of high speed CMEs had begun (Feynman and Hundhausen, 1994). During disk passage on rotation O (March) the activity center was the most prolific x-ray flare producer in the preceding 15 years. There were 35 class M flares and an additional 10 class X events. At least 195 individual optical flares were observed. The SPE was the largest that had occurred in 17 years. This SPE could not have been forecast on time scales of days to weeks because the re-energization of the activity center took place while it was on the far side of the Sun. It would have been necessary to view the far side of the Sun to forecast this event

Requirements for forecasting

- The above discussion shows that to forecast SPEs reliably on time scales of 2 to 20 hours, we must learn to forecast the occurrence of fast CMEs. If a CME has already taken place it is too late to forecast on this time scale. To forecast CMEs we must identify the conditions on the Sun that lead to the destabilization of corona] structures that become CMEs. Two important conditions leading to CMEs have already been identified, shearing of the large scale weak coronal magnetic fields that destabilize to become CMEs and the emergence of new magnetic flux within the 2 or 3 days prior to destabilization (Feynman and Martin, 1995). However, much more empirical study is needed before we have enough data and understanding to develop a forecasting capability.

- To forecast major SPEs on time scales of many days to weeks we need to observe the far side of the Sun. There is no other way that this goal can be accomplished

A Suggested Solution--MagSonas

An opportunity to begin to develop our forecasting capability on these time scales would be afforded by a spacecraft on the far side of the Sun. A low cost (SMEX class) mission called MagSonas (Magnetic Structures ON and Around the SLm) has already been proposed'. See Ruzmaikin et al. (1 997) for further information. Launched in 2001 and gradually increasing its angular separation from the Earth, the spacecraft would go behind the Sun (see figure 9). It carries a Doppler-magnetograph to image the solar surface throughout the mission and advanced radio communications to sound the inner corona from behind the Sun. The mission's scientific goal is to understand solar magnetic fields: their generation inside the Sun (dynamo) and appearance on its surface, and their influence on the corona and solar wind. The observations taken from MagSonas would be supplemented by observations taken from Earthside, either by existing spacecraft or from the ground.

MagSonas will allow several observations important for forecasting to be made. Early in the mission, when the Earth-Sun-MagSonas angle is less than 90 degrees (see figure 9), observations of the shearing of the weak fields that arc involved in CMEs can be made. These weak fields can not be observed by vector magnetographs. However, by combining line of sight magnetic field observations from two angles (MagSonas and Earth) information can be obtained on the shearing. This is the only way that has been suggested to obtain observations on the shearing of the weak magnetic fields. Later in the mission, when the Earth-Sun-MagSonas angle is greater than 90 degrees, the sources of CMEs can be continuously observed for months at a time. This is because the whole Sun can be viewed by combining MagSonas observations with routine Earthside observations. This period is called "whole Sun observations" in figure 9. When MagSonas is off the solar limb (called "CME" in the figure) it will view the solar surface beneath the CMEs observed by an Earthside mission such as SOI 10. in addition, when MagSonas is behind the Sun, radio sounding using polarized X and Ka band signals will permit the observation of magnetic fields within the corona before and during CMEs. Hundhausen (1 997) has identified knowledge ofthc magnetic fields in the corona as crucial to our ability to predict the occurrence and characteristics of mass ejections. MagSonas is designed to make this vital measurement.

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Figure Captions

1- The types of forecasts that will be required for manned space flight, (Adapted from a table in Foundations of Solar Particle Event Risk Management Strategies, 1996.)

2- The percentage of days in which the daily average flux exceeded 10 particles/s-cm^{-2}- sr in each year for the energy ranges indicated.

3- The flux of particles of energies > 10 MeV during the March, 1989 SPE. (Adapted from the GOES 7 data in Solar-Geophysical Data prompt reports, Dept. of Commerce.)

4- Transit time for protons from the Earth to the Sun. (From Barouch et al., 1971.)

5- Positions of the solar event marking the beginning of 7 major SPEs in the energy range of 10 to 60 MeV. (Data from Shea, this conference.)

6-1'0 make a week (two week) forecast of the SPEs in Figure 5, we would have needed to observe these source regions when they were at positions shown in the upper (lower) panel. This requires observations of the other side of the Sun.

7- Sunspot area at 60 degrees East and West of central meridian during 3 rotations of the active region causing the SPE shown in figure 3. Observations from this side of the Sun would not have been not sufficient for forecasting on "scheduled" time scales (see figure 1). Time is counted from first appearance of the activity center. The March SPE began a -55 days later, as the active region returned for the third time. See text for discussion.

8- The MagSonas trajectory taking the spacecraft around the Sun and stationing it on the other side. This trajectory was developed by Paul Penzo, let l'repulsion Laboratory.

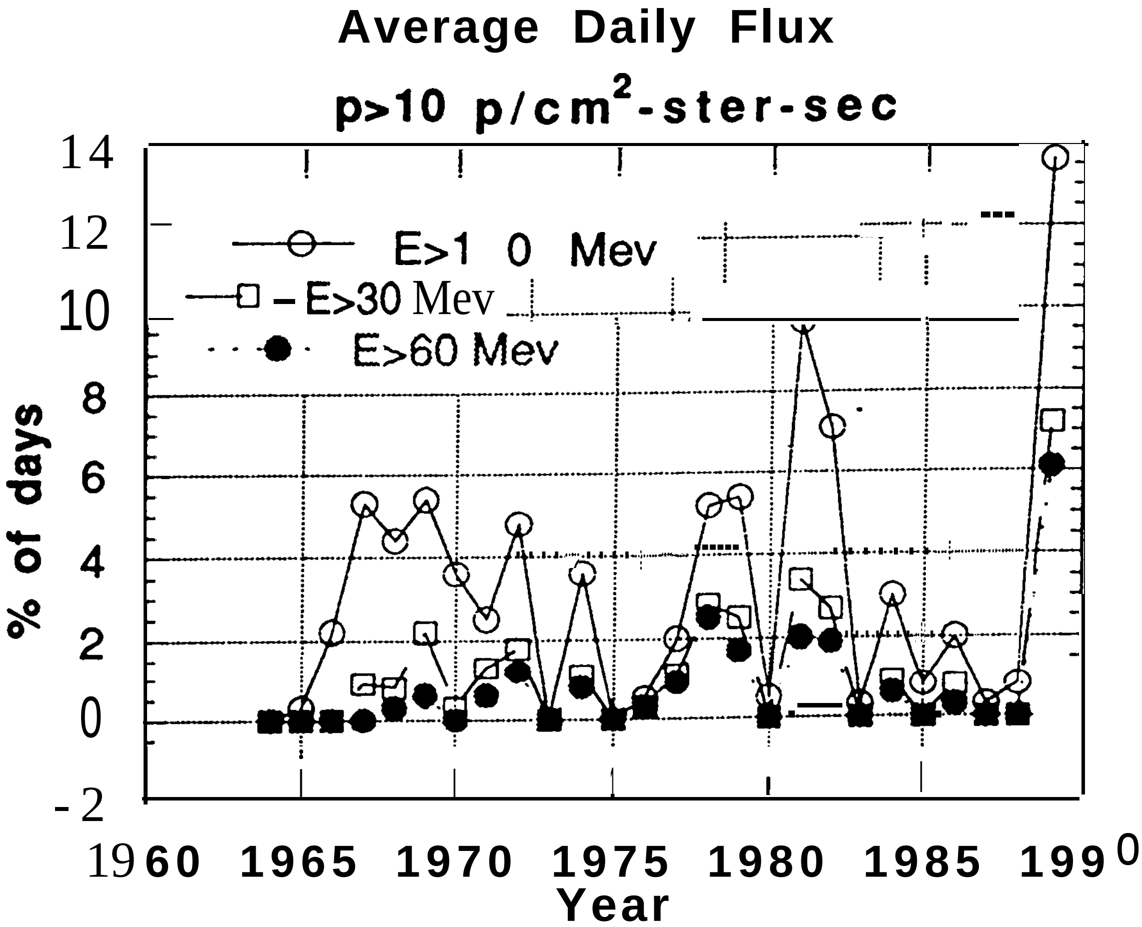
9- MagSonas opportunities for observations important to developing the capability to forecast SPE. Sec text for explanation.

Forecasts, lead times and capabilities *

Type of Forecast	**Lead time**	**status of Current Capability**
Climatology	Months-Years	Moderate
Scheduled	Days to Weeks	None
Event-triggered	2-20 hours	Moderate
Nowcast	10 minutes-8 hours	Low to moderate

*Adapted from Foundations of Solar Particle Event Risk Management Strategies, Findings of the 1996 Workshop.

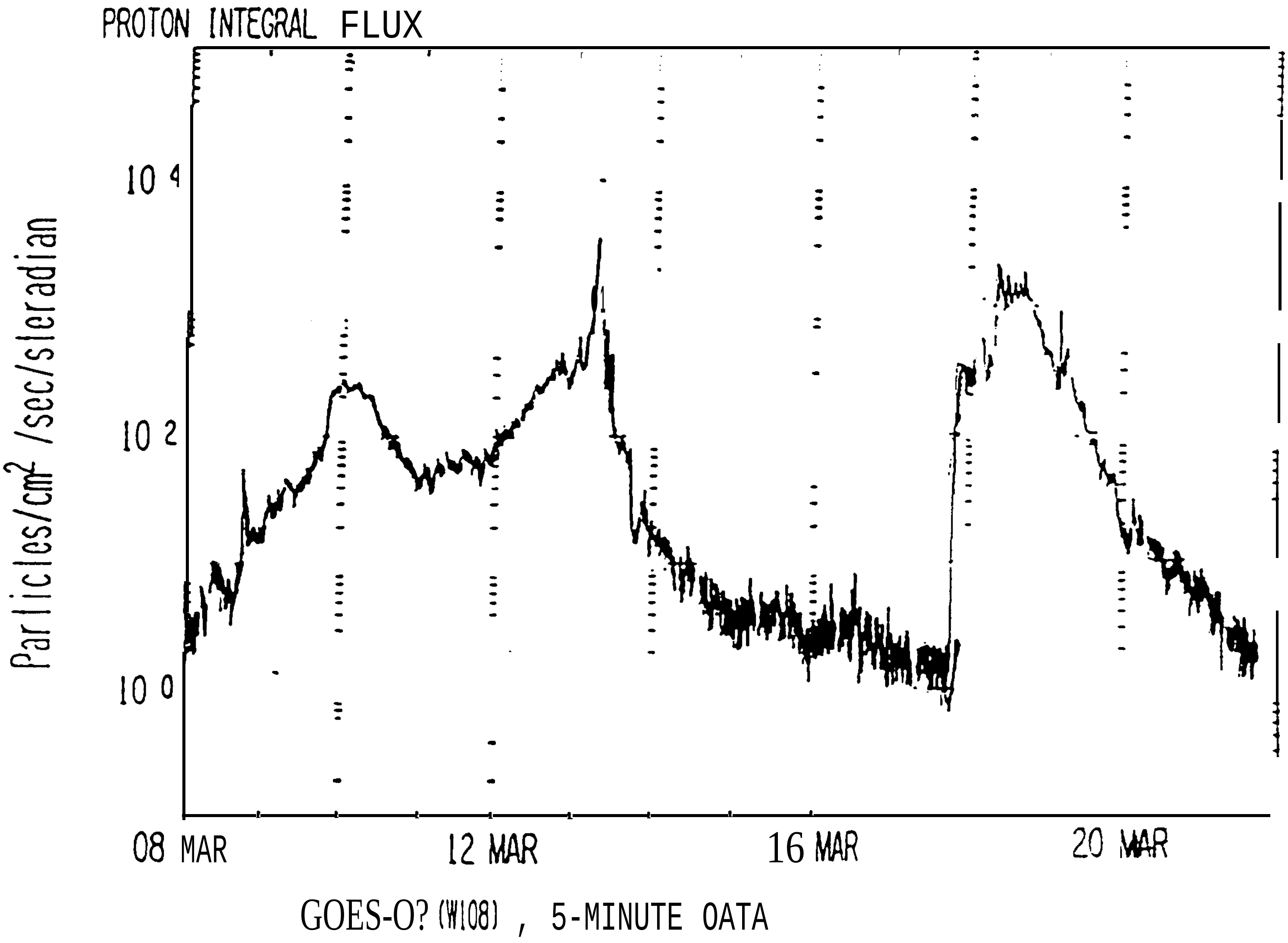
How Frequently is the Particle Flux High?



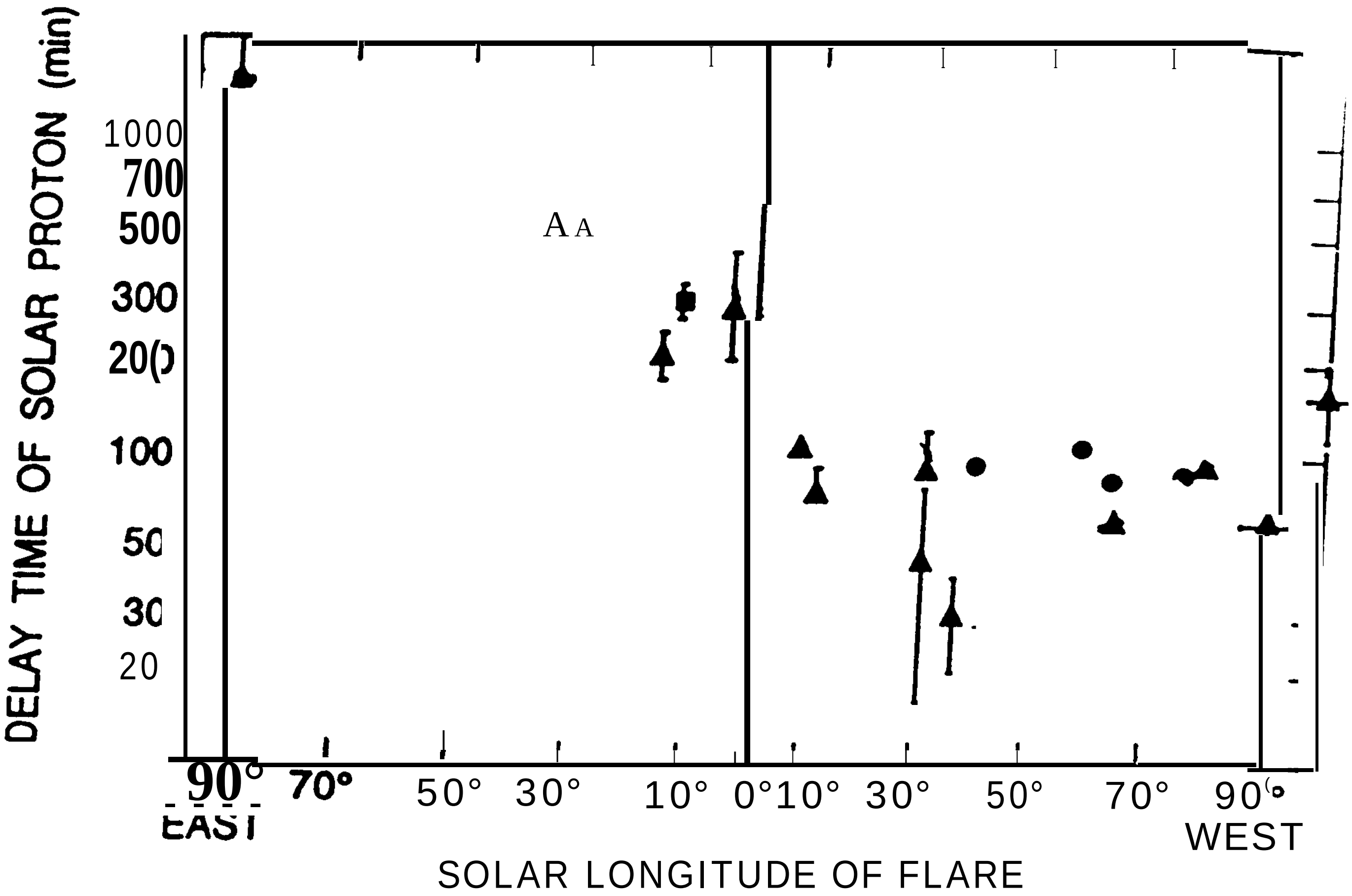
Percentage of days/year the daily average proton flux exceeds 10 particles/cm^2-ster-sec.

A Typical Event

Interplanetary Proton Event, March, **1989**

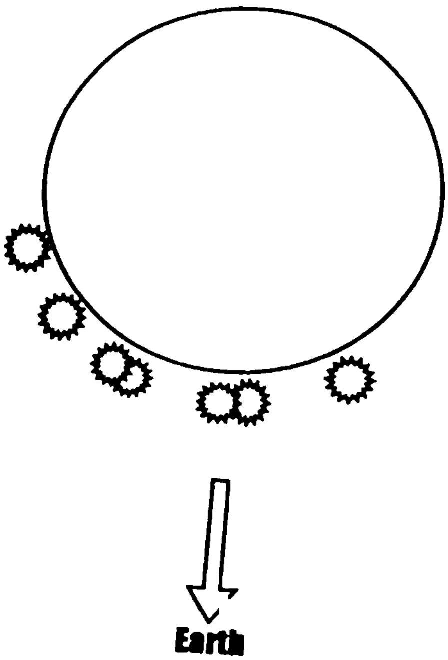


TRANSIT TIME FOR PROTONS FROM THE EARTH TO THE SUN



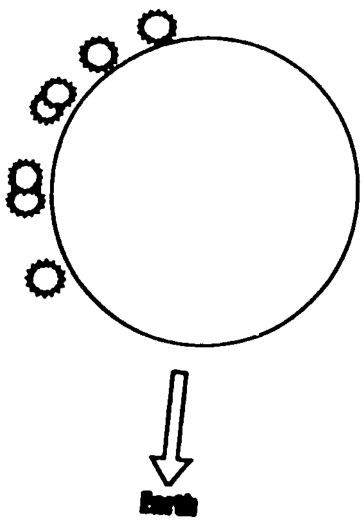
Data from Barouch et al., 197 I

Solar Source Positions as Seen from Earth



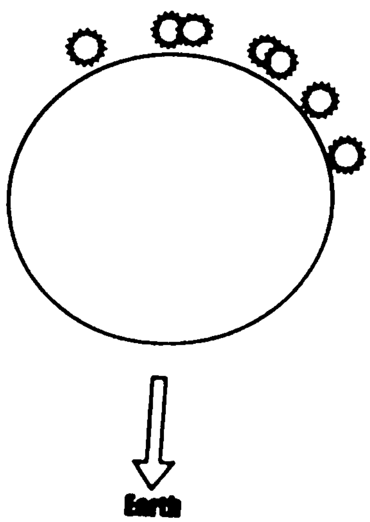
Forecast lead time-2 to 20 hr. requires capability to predict CMES

Solar Source Positions for "Schedule" Forecast Lead Times.



More than 1/2 Of the sources are behind the Sun's limb

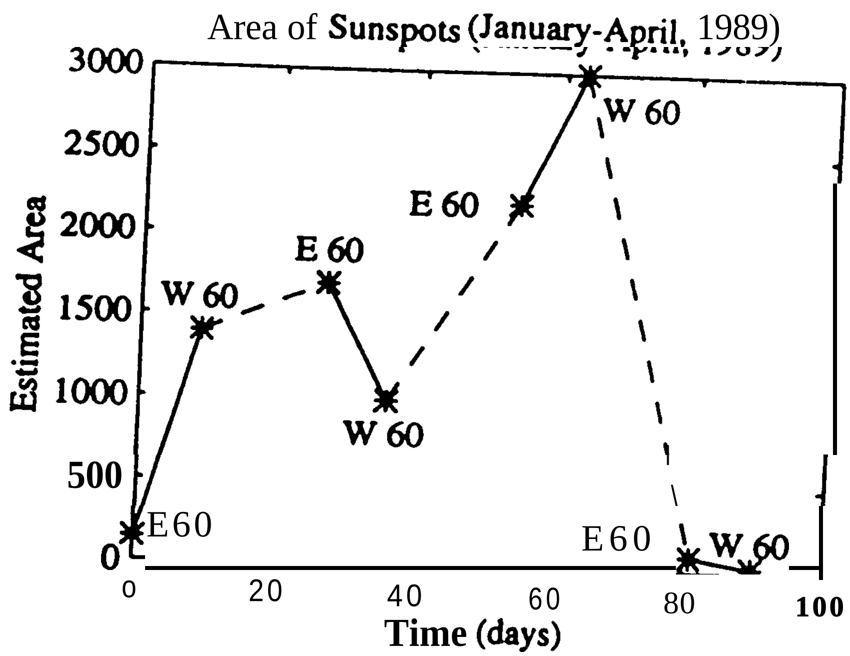
Forecast lead time- 1 week



All sources behind Sun's limb

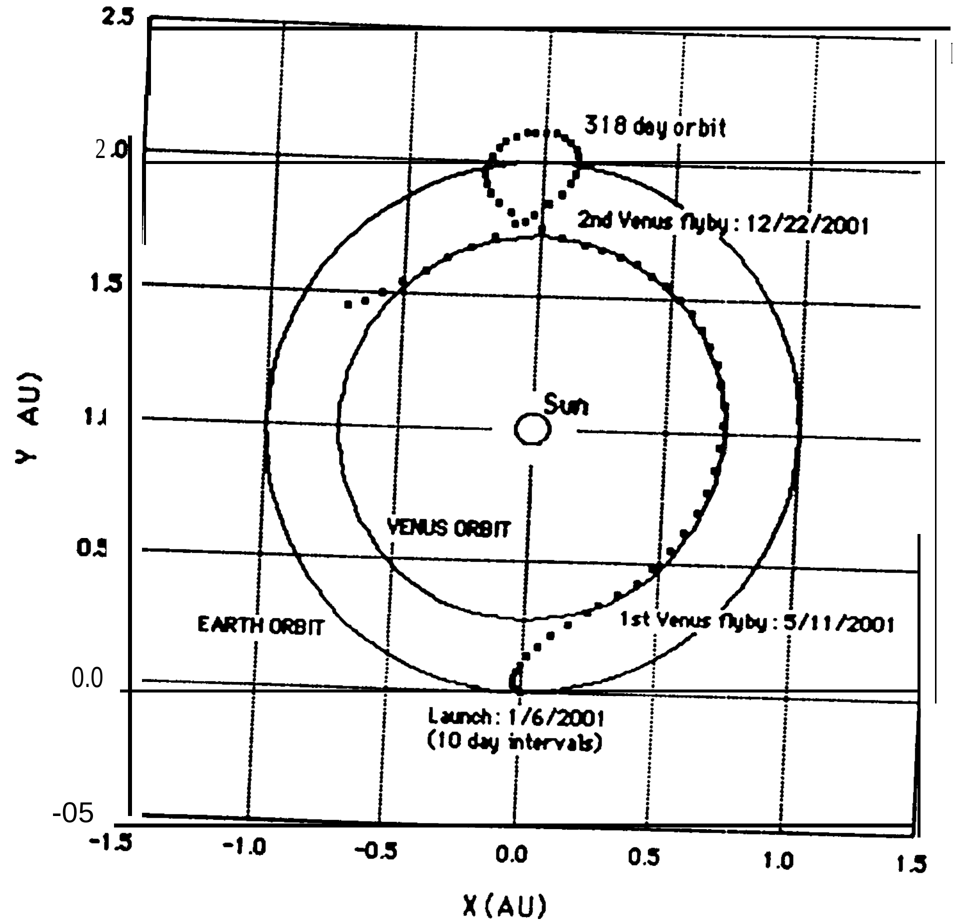
Forecast lead time- 2 weeks

Why We Can Not Forecast by Observing this Side of the Sun Alone.



Flux History of the Active Region Causing the March 1989 Event.

TRAJECTORY
view from above the ecliptic plane



OBSERVATION OPPORTUNITIES